Session 4: Performance measurements

COMP52315: performance engineering

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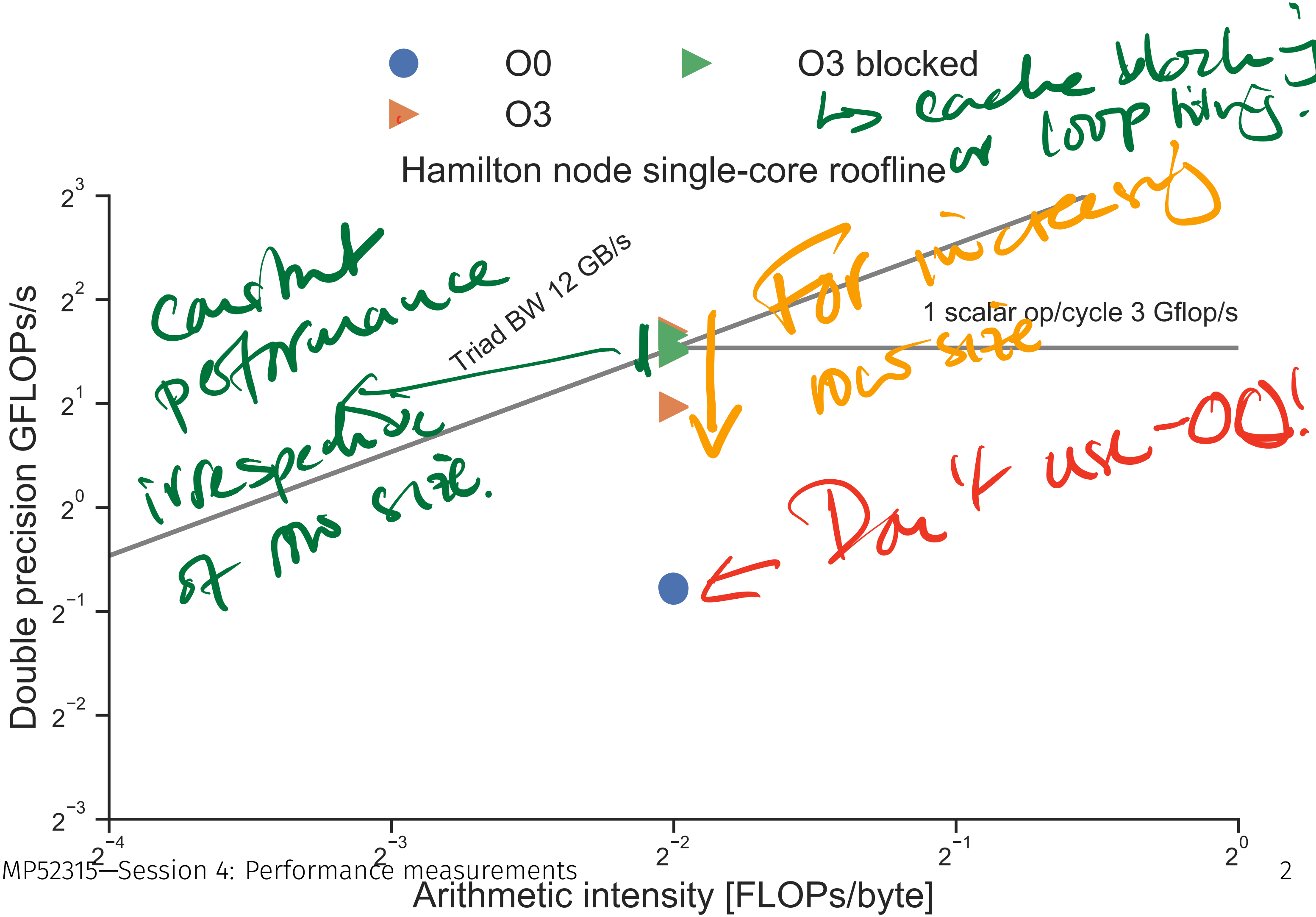
Roofline dense matrix-vector product



How and what to measure

- Roofline gives us a high-level overview of what to try next.
- How to drill down and get more information about what is causing the bottleneck?
- How to confirm the hypothesis formed through the roofline analysis?

$\Rightarrow$ *Measure* things about the code.

Performance measurements

Measure # floating point ops or cache misses or cycles

- Modern hardware comes with some special purpose *registers* that you can prod to measure low level performance events.
- Can use this to characterise performance of a piece of code

Caveats

- Measurements can only tell you about the algorithm you're using
- e.g. Counts the data you moved, not the data you could have moved.
- Do not tell you about potential better algorithms
- Need to work hand in hand with models.

motivates "perfect cache" model.

What kind of things can we measure?

- An almost overwhelming number of different things like:
    - Number of floating point instructions of different type (scalar, sse, avx)
    - Cache miss/hit counts at various levels
    - Branch prediction success rate
    - …

$\Rightarrow$ Best used to confirm hypothesis from some model

Abstract metrics

AVX instructions / cycle
memory reqs / cycle.

- Can read low-level hardware counters directly (e.g. how many floating point instructions were executed?)
- More useful to group into abstract metrices

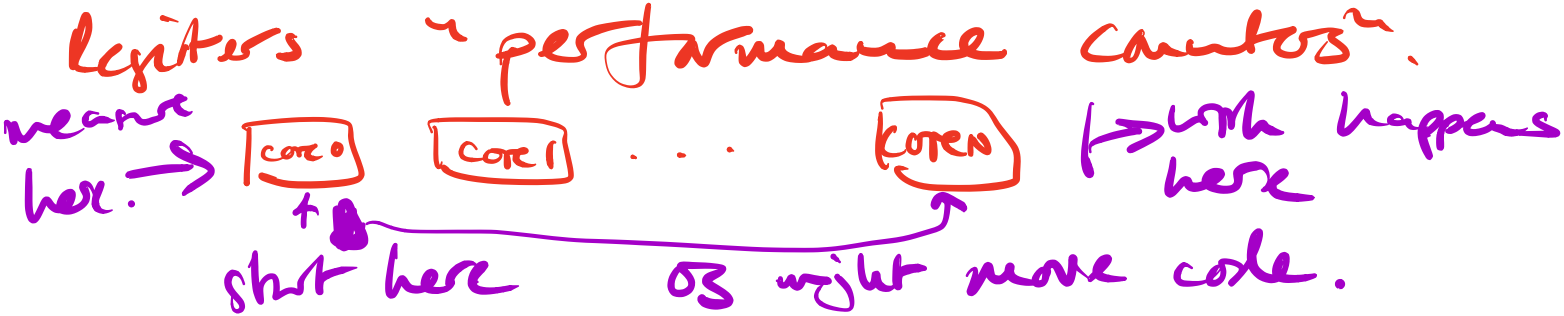
⇒ easier to compare across hardware, easier to interpret.

- For example, measure "Instructions per cycle" rather than instructions.

IPC.

takes frequency of CPU out of equation.

How do we measure them?



- Use `likwid-perfctr` (installed on Hamilton via the `likwid` module).
- Offers a reasonably friendly command-line interface.
- Provides access both to counters directly, and many useful predefined "groups".

Can use this to measure Operational intensity

⇒ compare with model.

Example: STREAM

a[i] = a[i] * b[i] + c[i]

- Will use **`likwid-perfctr`** to measure memory references in different implementations of the same loop.

Scalar

```
for i from 0 to n:
  load a[i:i+1] reg1
  load b[i:i+1] reg2
  load c[i:i+1] reg4
  mul reg1 reg2 reg3
  add reg4 reg3 reg4
  store reg4 c[i:i+1]
```

N iterations

SSE

```
for i from 0 to n by 2:
  vload a[i:i+2] vreg1
  vload b[i:i+2] vreg2
  vload c[i:i+2] vreg4
  vmul vreg1 vreg2 vreg3
  vadd reg4 reg3 reg4
  vstore reg4 c[i:i+2]
```

N/2 iterations

AVX

```
for i from 0 to n by 4:
  vload a[i:i+4] vreg1
  vload b[i:i+4] vreg2
  vload c[i:i+4] vreg4
  vmul vreg1 vreg2 vreg3
  vadd reg4 reg3 reg4
  vstore reg4 c[i:i+4]
```

N/4 its

AVX2

```
for i from 0 to n by 4:
  vload a[i:i+4] vreg1
  vload b[i:i+4] vreg2
  vload c[i:i+4] vreg3
  vfma vreg1 vreg2 vreg3
  vstore reg3 c[i:i+4]
```

N/4 its.

3 loads, 1 store / iteration.

Model

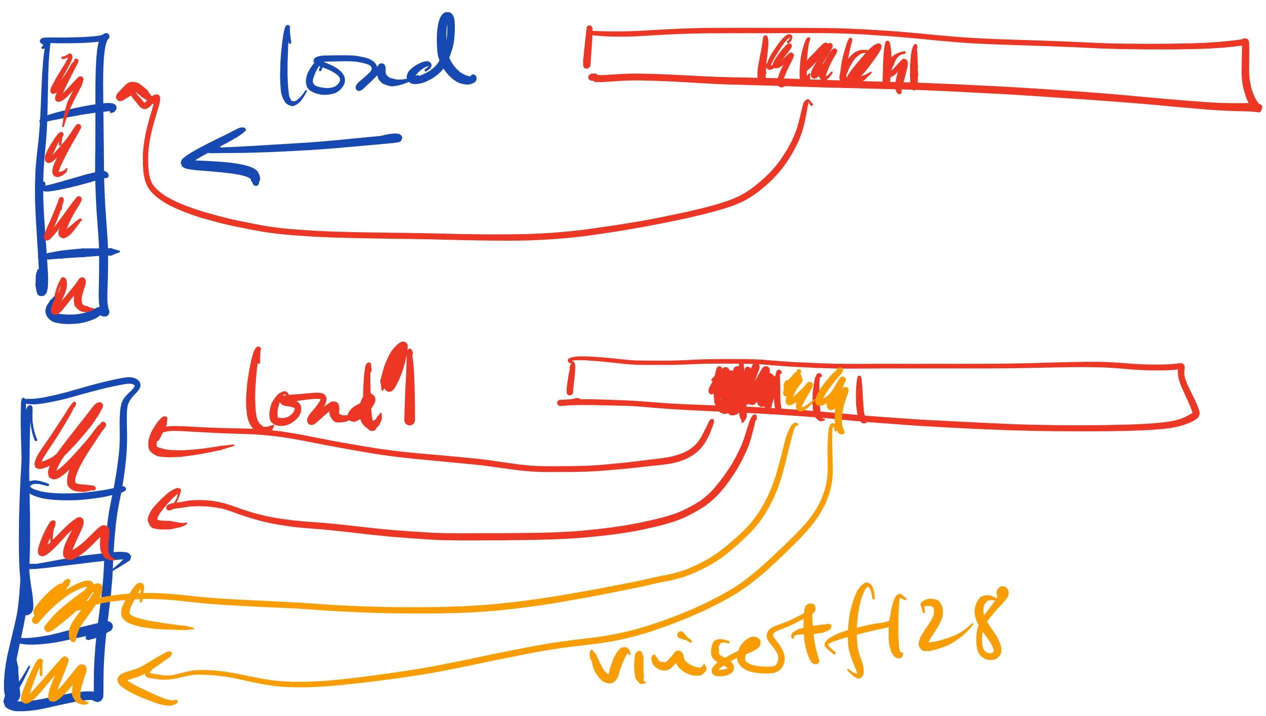
For each loop choice, if we choose $n = 10^6$, how many load and store instructions do we expect to measure?

Scalar: 3×10^6 loads
10^6 stores.

Aux: $\frac{3}{4} \times 10^6$ loads $\frac{1}{4} \times 10^6$ stores.

```
{
    LIKWID_MARKER_START("a")
    puta();
    LIKWID_MARKER_STOP("a");

    L_MARKER_START("b")
    putb();
    L_MARKER_STOP("b").
}
```



Measurement

Model

For each loop choice, if we choose $n = 10^6$, how many load and store instructions do we expect to measure?

Answer

Each loop iteration has 3 loads and 1 store.

Vector width v and n iterations we need $\frac{3n}{v}$ loads and $\frac{n}{v}$ stores.

$\Rightarrow$ let's attempt to verify this with measurements.

Exercise

- Goal is to convince ourselves that measurement works!

$\Rightarrow$ Exercise 5 from the usual place.

Exercises at

`https://teaching.wence.uk`

Larger code

Problem

What if you don't know which part of the code takes all the time?

Answer

Use *profiling* to determine hotspots (regions of code where all the time is spent).

$\Rightarrow$ allows us to focus in on important parts.

Profiling: types

- Goal is to gather information about what a code is doing
  - *Sampling* ← unmodified code (or even binary analysis)
  - or *code instrumentation*

  needs recompilation.

Sampling

- Works with unmodified executables
- Only a statistical model of code execution

⇒ not very detailed for volatile metrics

⇒ needs long-running application

→ Typical approach.

Instrumentation

- Requires source code annotations to capture "interesting" information
- ~~Much~~ Many more details and focused on particular region.

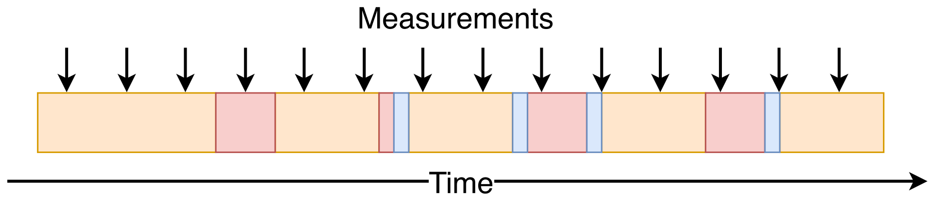
⇒ Preprocessing of source required

⇒ Can have large *overheads* for small functions.

→ often used if you need extra information. MPI-based

Sampling

- Running program is periodically interrupted to take a measurement.
- Records which function we are in.



Inspect stack frame to determine which function.

Typically sample every 1ms. (or more frequently if you know something).

```
void bar(...) {
   ...
}
```

```
void foo(...) {
   ...
   bar(...);
}
```

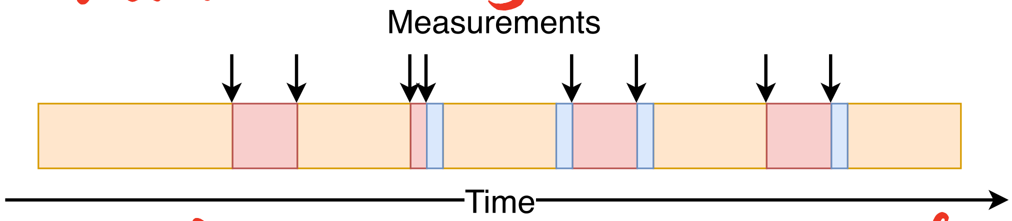
```
int main(void) {
   for (i = 0; i < N; i++) {
      if (i % 3 == 0) {
         bar(...);
      } else {
         foo(...);
      }
      ...
   }
}
```

... → 70%

Build up statistical model of the map code line → time.

- Measurement code is inserted to capture all the events we care about

example MPI-tracing.



More expensive than sampling.

Can skew time if overhead of measurement is large.

```
void bar(...) {
    ...
}
```

```
void foo(...) {
    Enter("foo");
    ...
    bar(...);
    Exit("foo");
}
```

```
int main(void) {
    for (i = 0; i < N; i++) {
        if (i % 3 == 0) {
            bar(...);
        } else {
            foo(...);
        }
        ...
    }
}
```

foo: 100ns

overhead required ~ 40ns

tmp = expensive();
Exit(...)
return tmp;

Also "count" events.

modify program state (eg. caches) → likwid_MarkerStart(R1)

what to measure there,
but also performance counters here

likwid_MarkerEnd(R1)

. . .

likwid_mstart(R4)

. . .

likwid_mstop(R4)

R1: some data

R4: other data.

Sampling profiles with gprof

Python: pyspy ; pyinstrument ← samples

→ pip packages

annotate/tracing: cProfile library ← builtin

Workflow

1. Compile *and link* code with symbols (add `-g`) and profile information (`-p`).
2. Run code ⇒ produces file `gmon.out`
3. Postprocess data with `gprof`
4. Look at results

debug symbols → records function names for tools to use.

automatically adds events (start/stop) to function definitions

On linux-based systems.

perf ← statistical profiler. → needs kernel module + setuid root.

→ profiles assembly

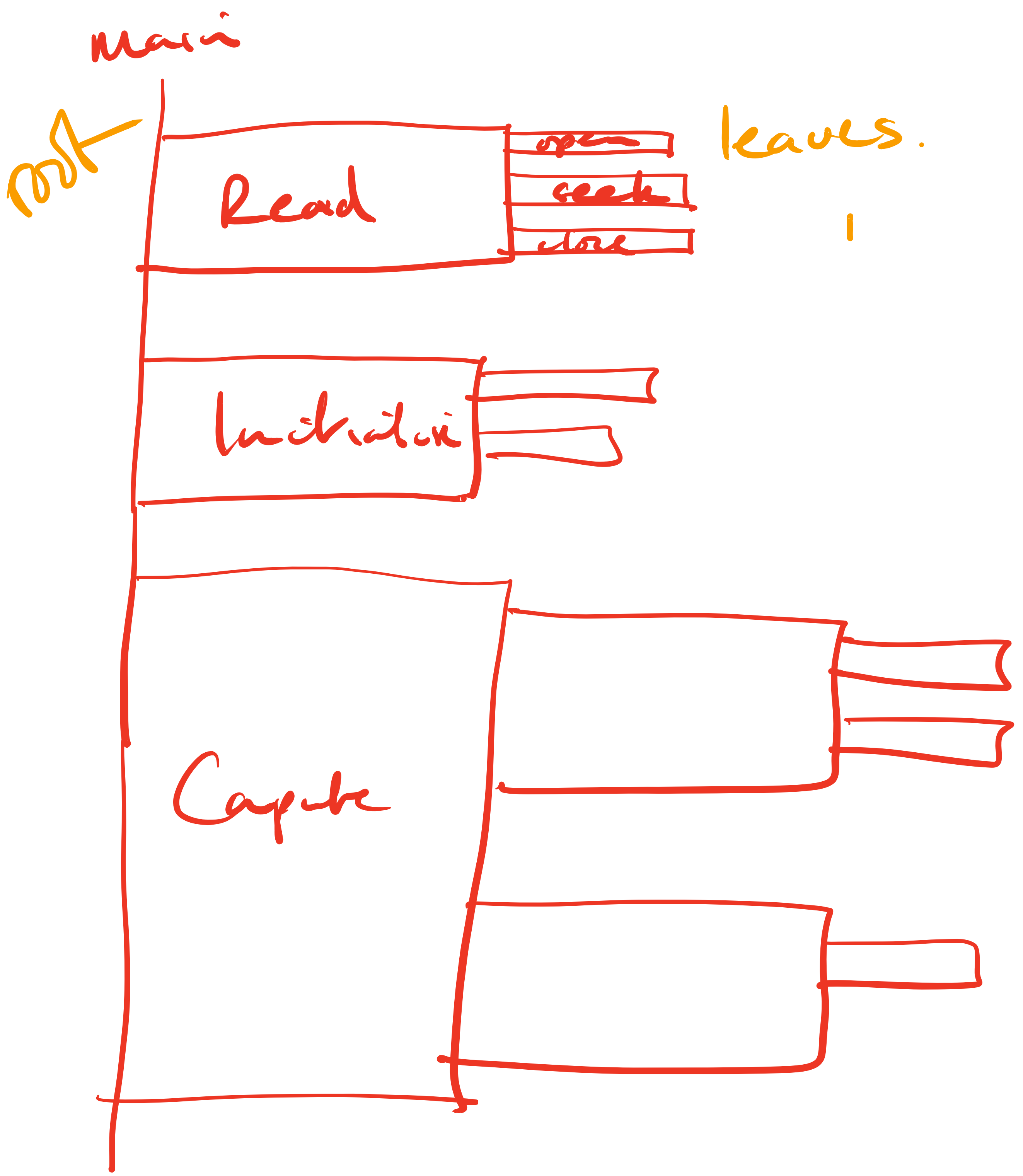
if symbols/debug info is available it can also assign time to lines of code.

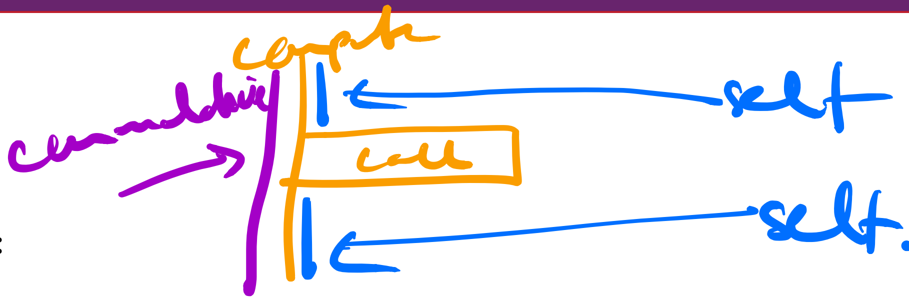
↳ lots of 3rd party tooling built on top.

Windows/MacOS: I don't know sorry!

Commercial tools: so Intel VTune has a bunch of stuff.

Gprof: sampling profiles but with complete call tree.






```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls   s/call   s/call  name
 76.14      5.71     5.71      102     0.06     0.06  ForceLJ::compute(Atom&, Neighb
 17.07      6.99     1.28        6     0.21     0.22  Neighbor::build(Atom&)
  2.80      7.20     0.21        3     0.07     0.07  void ForceLJ::compute_halfnei
  1.47      7.31     0.11        1     0.11     7.05  Integrate::run(Atom&, Force*,
  0.93      7.38     0.07                             __intel_avx_rep_memcpy
  0.40      7.41     0.03       11     0.00     0.00  Neighbor::binatoms(Atom&, int)
  0.40      7.44     0.03        6     0.01     0.01  Comm::borders(Atom&)
  0.40      7.47     0.03        1     0.03     0.04  create_atoms(Atom&, int, int,
  0.13      7.48     0.01   285585     0.00     0.00  Atom::unpack_border(int, doub
```

Also call-tree based profiles.

gprof "flat profile"

- Code is instrumented (instructions inserted so we know which function we're in), triggering of measurement is sampling based (not every call).
- GProf provides profile with some tracing information
- Gives both *inclusive* and *exclusive* timings.

- Blue box shows "inclusive" time for `main`
- `foo` and `bar` calls (orange) excluded for "exclusive" time.

⇒ exclusive time measures execution in function that is not attributable to some other function.

```
int main(void) {
    for (i = 0; i < N; i++) {
        if (i % 3 == 0) {
            bar(...);
        } else {
            foo(...);
        }
        ...
    }
}
```

Continued workflow

- After we have identified the hotspot that takes all the time, we'd like to determine if it is optimised

⇒ need more detailed insights.

1. Find relevant bit of code
2. Determine algorithm ← read it.
3. Add instrumentation markers (see exercise) ← likwid markers
4. Profile with more detail/use performance models.

⇒ guidance for appropriate optimisation.

Exercise: finding the hotspot

- So far, we've looked at very simple code. Now, your task will be to find the hotspot and do some exploration in a larger one.

$\Rightarrow$ Exercise 6 from the usual place.

Exercises in the usual place at

`https://teaching.wence.uk`